Testing Enabling Technologies for Safe UAS Urban Operations

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A set of more than 100 flight operations were conducted at NASA Langley Research Center using small UAS (sUAS) to demonstrate, test, and evaluate a set of technologies and an over-arching air-ground system concept aimed at enabling safety. The research vehicle was tracked continuously during nominal traversal of planned flight paths while autonomously operating over moderately populated land. For selected flights, off-nominal risks were introduced, including vehicle-to-vehicle (V2V) encounters. Three contingency maneuvers were demonstrated that provide safe responses. These maneuvers made use of an integrated air/ground platform and two on-board autonomous capabilities. Flight data was monitored and recorded with multiple ground systems and was forwarded in real time to a UAS traffic management (UTM) server for airspace coordination and supervision.

I. Nomenclature

AGL = height above ground level
DSRC = dedicated short range communications
GCS = ground control station
ICAROUS = independent configurable architecture for reliable operations of unmanned systems
RFI = radio frequency interference
sUAS = small unmanned aerial system
UAS = unmanned aerial system
UTM = UAS traffic management
V2V = vehicle-to-vehicle

II. Objectives

Enabling the safe operation of small UAS vehicles in uncontrolled airspace is a major goal of NASA's Unmanned Aerial System (UAS) Traffic Management (UTM) project [1][2]. The UTM project particularly emphasizes the advancement of research on UAS tracking, autonomy, and navigation at low altitudes as well as technologies to enable beyond visual line-of-sight operations at these altitudes. Many of the required advancements are encompassed in the project's demonstration milestone, UTM Technology Capability Level 3 (TCL-3), which calls for:

- demonstrations of continuous vehicle tracking during beyond visual line-of-sight operations over moderately populated land;
- advanced communication capability including vehicle-to-vehicle (V2V) and vehicle-to-tracking-system (V2UTM) links; and,
- well-defined reference missions such as public safety, infrastructure inspection, and package delivery missions.

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These TCL-3 characteristics served as drivers for the flight research described in this report. Objectives of the testing were specified as follows:

1) Perform a series of autonomous flights emulating various low altitude urban sUAS missions and off-nominal situations; thereby establishing a baseline set of data to serve as a foundation for future R&D including urban air mobility.
2) Evaluate the maturity of new systems being investigated as enablers (i.e., systems to mitigate public safety risks that may otherwise constrain operations), with an emphasis on no-fly zone avoidance, degraded GPS resilience, real-time risk assessment diagnostics, and autonomous initiation of contingency procedures or maneuvers that avoid such hazards.

III. System Description and Research Technologies

In addition to commercial off-the-shelf sUAS elements (e.g., autopilot and GCS software), four advanced airborne and ground system functions were deployed to achieve the research objectives.

Onboard the vehicle, these advanced functions included:

1) ICAROUS, a decision-making framework and technology that provides autonomous contingency management when near hazards or operational constraints (e.g., no-fly zones) [3].
2) Safeguard, an independent geo-conformance monitor that provides warning and terminate signals to a decision-making function and termination mechanism, respectively [4][5]. Safeguard also provides a "black-box"-like data recording function.
3) A Locata positioning system receiver that provides independent position estimation for testing resilience to GPS-degraded situations [6].
4) A Dedicated Short Range Communications (DSRC) system that provides vehicle-to-vehicle position, heading and velocity estimates to an ICAROUS-based detect-and-avoid function.

On the ground, these advanced functions included:

1) Safeguard and ICAROUS support tools that provide pre-flight, in-flight, and post-flight functions. For example: constraint loading and flight preview (pre-flight), state monitoring (in-flight), and data archiving (post-flight).
2) A Locata portable local positioning system that provides independent position estimation for testing resilience to GPS-degraded situations [6]. This consists of a set of transceivers installed at various locations in the vicinity of the flights.
3) A UTM-connected client application that requests airspace access, relays the vehicle identification and position for continuous tracking, and receives UTM-generated airspace access time windows and relevant alerts [7].
4) A prototype Real-Time Risk Assessment (RTRA) tool that monitors aircraft telemetry to collect candidate ensembles of conditions and advises the operator of predicted risks along the planned route of flight [8].

An integrated air/ground platform, developed initially for an autonomous infrastructure inspection mission [9][10], was used to operate the aircraft, plan flights, and collect vehicle position telemetry for UTM tracking and forwarding to other ground systems. Two links were used to connect the ground system to the airborne system: (1) a 2.4 GHz link for safety pilot command-and-control and (2) a 900 MHz link for ground control station (GCS) command-and-control and data telemetry. Video telemetry was not utilized.

ICAROUS is a software architecture that enables the robust integration of mission specific software modules and highly assured core software modules for building safety-centric autonomous unmanned aircraft applications. The set of core modules include formally verified algorithms that detect, monitor, and control conformance to safety criteria; avoid stationary obstacles while maintaining a safe distance from other users of the airspace; and compute resolution and recovery maneuvers that are autonomously executed by the autopilot when safety criteria are violated or about to be violated. ICAROUS uses Ardupilot's MAVLink [11] protocol to communicate with the autopilot. ICAROUS software is publicly available under NASA's Open Source Agreement.

Safeguard monitors and predicts non-conformance with geospatial stay-in and stay-out regions. The device is isolated and independent of the aircraft's autopilot and operating system. The current design requires no inputs from a communication link or any onboard systems during flight. The Safeguard unit under test produces two output signals. The first provides a warning of predicted violations to allow the autopilot an opportunity to take action to avoid a violation (e.g., change course or hold in position). The second signals that the vehicle is not responding appropriately to the warning and that a violation is imminent. This signal may be utilized in various ways (e.g., trigger auto-land immediately, or cut power to the motors), or it may not be used at all, depending on mission and safety requirements regarding the risk of entering no-fly zones.

Dedicated short range communications (DSRC) systems operating in the 5.9 GHz frequency band have been developed for the automotive industry to provide safety data links to drivers that warn of other vehicles [12]. In this flight research, they provide an inter-vehicle data link to report position, heading, and velocity. Onboard computing can harness this information to avoid collision with aircraft in nearby airspace; the reception of a DSRC signal from other aircraft and the resultant computation for collision avoidance together form a viable sense and avoid (SAA) method [13]. DSRC is an alternative to the widely-deployed Automatic Dependent Surveillance-Broadcast (ADS-B) systems used in manned aircraft. ADS-B systems continuously broadcast the vehicles' location to other aircraft and to ground-based transceivers that route the data to Air Traffic Control [14]. The ADS-B system is designed to handle commercial and general aviation traffic volumes, but the volume of future sUAS operations is projected to exceed its capacity [15]. With its shorter (roughly 0.5 km) range at low altitudes, DSRC radio signals will not extend beyond the local airspace of an sUAS and therefore will not overwhelm aviation spectral bands in the airspace with irrelevant data streams. To advance operational understanding of ADS-B alternatives, DSRC-based collision avoidance was integrated into the flight platform as follows. Each aircraft was outfitted with a Unex OBU-201 DSRC device, and the ICAROUS software was modified to interpret the DSRC-reported position, heading, and velocity of nearby aircraft.

For this series of tests, two identical octocopter frames (i.e., body frame, motors, and propellers) were outfitted with a Pixhawk [16] autopilot, a GPS receiver and 900MHz radio from 3DRobotics, a 2.4 GHz remote control receiver, two dedicated processors for additional control and sensor collection [10], the self-contained Safeguard unit [5], and the Unex OBU-201 DSRC device. The autopilot was in continuous two-way communication with a GCS computer running a version of APMPlanner2 mission planning and operation software [17]. ICAROUS was installed on a dedicated processor board and was in continuous two-way communication with the autopilot and GCS. In this configuration, both the GCS and ICAROUS could command the UAV's autopilot, for example, to go to a specific GPS coordinate with a specific velocity and altitude.

ICAROUS received the warning and terminate signals from Safeguard via a dedicated two-wire digital connection, and position/velocity reports from nearby aircraft via the DSRC unit. The off-the-shelf Locata receiver and a video camera were also installed to complete the payload (~22 lbs.). As a precaution in case of avionics malfunctions, GCS and ICAROUS control lines were routed through a radio-controlled "kill switch" available to a remote-control (RC) safety pilot. A system diagram is shown in Figure 7.

For vehicle-to-vehicle encounters, a Tarot hexacopter served as the "rogue vehicle" and was outfitted with a Pixhawk autopilot, a GPS receiver, a 900MHz telemetry radio, a 2.4 GHz remote control receiver, and a Unex OBU-201 DSRC device [13].

Selected flights were tracked using the NASA UTM client-server capability over a cellular TCP-IP connection between the client (running on a laptop connected via Ethernet to the GCS computer) and a server (located at NASA Ames Research Center).

IV. Research Flight Locations and Operations

In total, 123 research flights were conducted from June 2017 to March 2018 at NASA Langley Research Center's City Environment for Range Testing of Autonomous Integrated Navigation (CERTAIN). A primary flight range consisting of a 1.14 km path over streets within the CERTAIN range was selected for most operations (Figure 1). Two secondary ranges at off-street sites were also selected: a large gantry structure typically used for aircraft crashworthiness testing and a large building construction site. Within the primary range, flight altitude was typically 20-40m. In the secondary ranges, vertical profiles (climbing/descending) were emphasized to test 3D positioning fidelity, and altitudes ranged up to 100m.

The series included four broad classes of autonomous flights:

1) Waypoint-to-waypoint flights centered on a straight path overflying streets and at constant altitude
2) Waypoint-to-waypoint flights around or within the perimeter of street boundaries
3) Waypoint-to-waypoint flights avoiding a stay-out geofenced obstruction or high-risk area
4) Waypoint-to-waypoint flights avoiding a nearby aircraft

For the third class, three contingency maneuvers were tested:

A) Bounce-back. In response to a Safeguard-generated proximity warning, ICAROUS directs the autopilot to fly backward along the approach path and away from the stay-out region.

B) Auto-land. In response to a Safeguard-generated terminate signal, ICAROUS directs the autopilot to land before entering the stay-out region.

C) Circumnavigate. When approaching a stay-out region, ICAROUS takes control from the autopilot (“guided mode”) and commands a re-route around the stay-out region, maintaining a minimal safe standoff distance, and then returning control to the autopilot (“auto mode”) for continuing flight to the next waypoint in the flight plan.

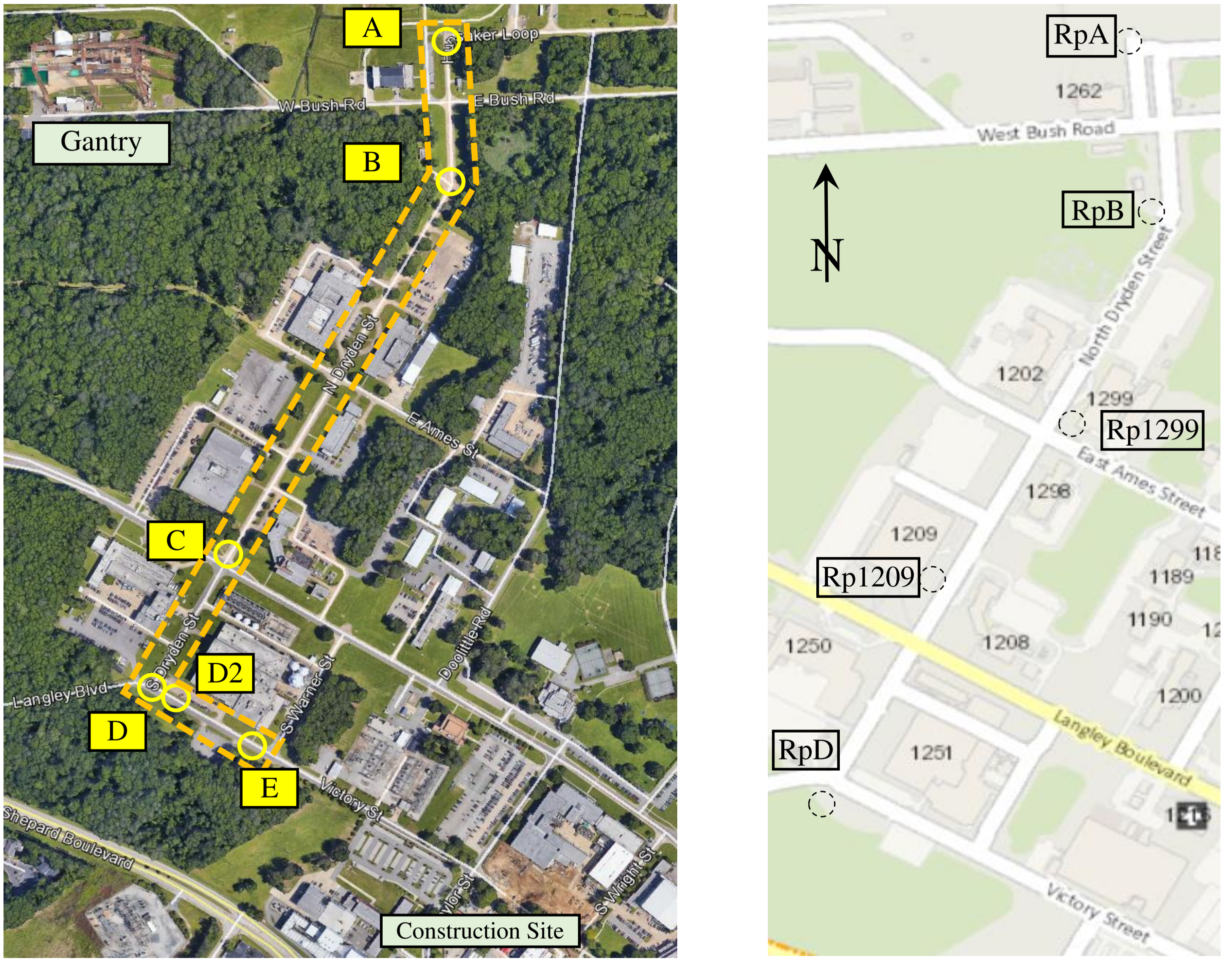

Figure 1. Flight range for operations over streets. Left: Satellite view showing polygonal keep-in geofence (dashed orange line) and waypoints (yellow circles) of the primary flight range. Yellow boxes contain the waypoint designators. The two secondary ranges are labelled with green boxes. Right: Street view showing rally points along the primary range. © *Satellite map data: Google. Street map data: NASA*

For the fourth class, the circumnavigate maneuver was exercised when loss of separation was detected. However, since the rogue aircraft was moving, the circumnavigation path could vary based on the encounter geometry and closure rate.

Using one or more of these four classes as a basis, the following types of tests were defined to achieve the objectives described in Section II.

a) Calibration and system integration tests
b) Conformance violation tests (auto-land)
c) ‘Bounce-back’ tests
d) Re-route tests
e) Stand-off and UV corona tests
f) GPS/local positioning system tests (2 locations)
g) Multi-aircraft encounter tests (including V2V technology)
h) Multi-segment tests (beyond line-of-sight of GCS)
i) Tracking in National Air Space

Most tests were flown autonomously (i.e., on autopilot). As a precaution, an RC-based safety pilot monitored the flights and was able to intervene if there were an unexpected failure condition.

Table 1 summarizes the completed flights. For each date, it lists the number of flights completed, which technologies were employed, which segment or location was used, and which test or test class was used (per the coding above).

Table 1. Flight dates, technologies, operations[1] and locations.

Date	# Flights	Technology employed						Operation class/type	Segment or Location
		Icarous	Safeguard	UTM	Locata	UV Sense	DSRC		
2017_06_09	4							1,2/a	Victory St.
2017_06_21	7							1,2/a	Victory St.
2017_06_27	10		x					1,2/a	Victory St.
2017_07_12	6	x	x					1,3/b,c	S. Dryden St.
2017_07_15	6	x	x					1,3/b,c	S. Dryden St.
2017_07_18	7	x	x					1,3/b,c	S. Dryden St.
2017_07_20	9	x	x	x				1,3/b,c,d,i	S. Dryden St.
2017_08_01	4	x	x			x		1,2/a,e	N. Dryden St.
2017_08_03	8	x	x		x			1,2/a,f	N. Dryden + S. Dryden
2017_10_25	10							1,2/a	Certain 1 + N. Dryden + S. Dryden
2017_10_27	5							1,2/a	Certain 1 + N. Dryden + S. Dryden
2017_11_03	7	x	x					1,2/a,h	Certain 1 + N. Dryden + S. Dryden + Victory
2018_01_24	5			x	x			1,2/f,i	Gantry
2018_02_09	4	x	x	x				1,3/a,d,h,i	Certain 1 + N. Dryden + S. Dryden + Victory
2018_03_19	8		x	x				1,2/a, i	Construction site
2018_03_28	23	x	x				x	1,3,4/a,c,d,g,h	Certain 1 + N. Dryden + S. Dryden + Victory

Over the course of the testing, segments along and within the primary flight range were flown for some of the tests, varying in length from 1-2 city blocks. Specifics are given in Table 1 by street name. Multiple tests were flown on most segments, including calibration (aerial range survey) flights to verify, for example, that GPS was available and that there was no strong radio inference within the control and telemetry bands.

Upon successful calibration flights of the first two segments (Victory Street, points D to E of Figure 1 and South Dryden Street, points C to D of Figure 1), several of the contingency maneuvers were tested in the series beginning on 2017_07_20. A stay-out region was constructed at the intersection of Langley Boulevard and Dryden Street (point C of Figure 1) and the waypoints of the UAV flight plan were defined such that the UAV encountered the geofence

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[1] Classes of autonomous flights:
1) Waypoint-to-waypoint flights centered on a straight path overflying streets and at constant altitude
2) Waypoint-to-waypoint flights around or within the perimeter of street boundaries
3) Waypoint-to-waypoint flights avoiding a stay-out geofenced obstruction or high-risk area
4) Waypoint-to-waypoint flights avoiding a nearby aircraft

Types of tests:
a) Calibration and system integration tests
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c) 'Bounce-back' tests
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g) Multi-aircraft encounter tests (including V2V technology)
h) Multi-segment tests (beyond line-of-sight of GCS)
i) Tracking in National Air Space

at cruise altitude and speed. Figure 2 shows the geofenced stay-out region and the telemetry (from the autopilot and the UTM server) for a typical test of the terminate maneuver (i.e., auto-land). The loaded flight plan consisted of a takeoff from waypoint 1, an ascent to a twenty meter height above ground level (AGL) altitude at waypoint 2, and a traversal at this fixed altitude to waypoint 3 followed by a landing at waypoint 3 (red diamonds). The vehicle position, as reported every half second by the autopilot, is shown in green and yellow. This vehicle position was forwarded to the UTM tracking server approximately every 3 seconds. Tracking positions retrieved from the UTM server after the flight are shown as grey spheres. A stay-out geofenced region (cyan) was created in the middle of a street intersection between waypoints 2 and 3. Upon approaching the geofence (green position series), the avionics detected an imminent violation (per the Safeguard design) and initiated an auto-land (yellow position series).

Figure 2. Example of a flight ending with an auto-land contingency maneuver to avoid geo-fence violation at street intersection. This flight included UTM tracking (Flight date 2017_07_20). Waypoints are shown as red diamonds. Vehicle positions as reported by the autopilot are shown as green and yellow lines extending from the vehicle altitude to ground. Vehicle positions as retrieved from the UTM tracking server are shown as grey spheres. The stay-out region is shown as the cyan box at middle left. Upon approaching the geofence (green position series), the Safeguard avionics detected an imminent geofence violation and initiated a landing (yellow position series). © *Satellite map data: Google.*

Some testing on the North Dryden segment (points B to C in Figure 1, row 2017_08_03 of Table 1) was conducted using a portable set of Locata transceivers placed adjacent to the roadway. Analysis is underway to compare GPS, IMU, and the Locata-derived position information from those flights.

For other tests, a low-altitude "lawn-mower pattern" was flown at several altitudes above an ultraviolet generator calibrated to emit with a strength equal to coronal radiation of a damaged 100 kV electrical transmission line [18][19]. A corona source fastened to tripod was placed at a known location (top left of Figure 3), and a set of zigzag waypoints was created within a 7.5m x 7.5m box centered on that location at three elevations (3m, 5m and 7m) above the source. UV signal strength was transmitted to the ground station as the UAV traversed these waypoints. After the flight, telemetry was corrected for UAV attitude and converted to kml format. A one meter line representing UV sensor direction was constructed extending from the UAV position in the body frame of the aircraft and rotated to the earth frame using yaw, pitch, and roll intrinsic Tait-Bryan angle rotations [20]. The color of the placemark and the sensor direction line was set on a gradient scale from green to red based on the UV signal strength: green at the minimum strength of 1-2Hz and red at the maximum strength of 11-12Hz. A signal strength of 0Hz (no signal) was colored grey. The results are shown at the bottom left (top-down view) and right (side view) in Figure 3. At a distance of 9.1 m (30 feet; out of frame), the measured UV intensity matched the calibrated response level for sensor. Signal magnitude varied with distance and pointing angle as expected.

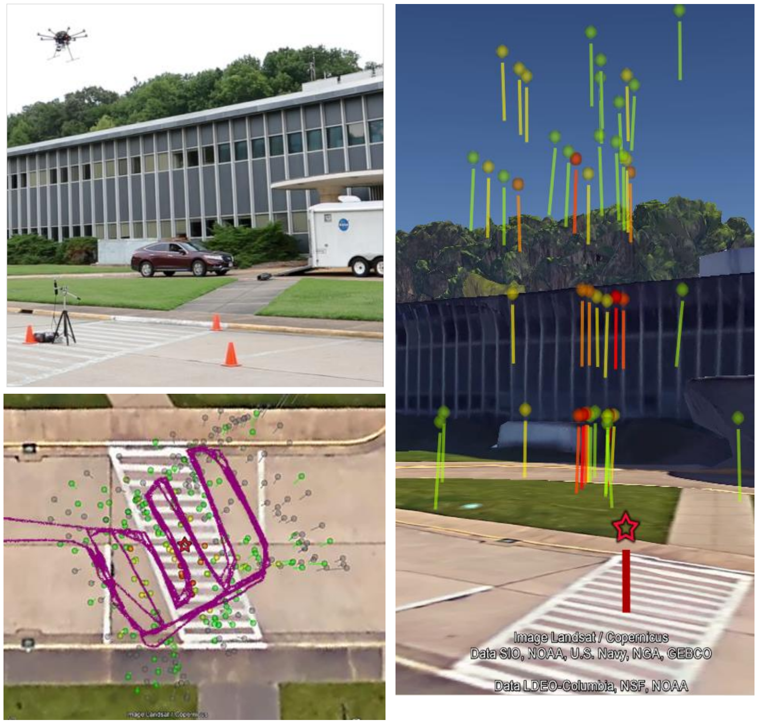

Figure 3. Ultraviolet source location research flight from the flight date 2017_08_01. Top left: video frame from 2m/s autonomous flight. Bottom left: top-down rendering of flight telemetry, with purple trace indicating UAV position and colored spheres indicating measured UV intensity. The star indicates the UV source location. Right: side view. Measured UV intensity is indicated by color: 0Hz (grey), 1-12Hz (green-to-red color scale). Direction lines indicate the sensor attitude, and points with low UV count (0-2Hz) are removed in the view at right to reduce clutter. © *Map data: Google.*

For the long multi-segment flights, the geometry of the range is such that an RC-based safety pilot cannot maintain line of sight from any single position in the range. Since position B afforded the best line of sight of all points in the range, the GCS and starting safety pilot position were located there. Still, trees along the flight path attenuated the 2.4 GHz safety pilot command-and-control link at altitudes below 40 meters. Further, the building on Victory Street (near point D2 of Figure 1; and top of Figure 2) blocked reception at point B of both the 2.4 GHz safety pilot command-and-control link and the 900 MHz link for GCS command-and-control and data telemetry. For this reason, a chase vehicle method was used for these flights such that the RC-based safety pilot could maintain line-of-sight.

The first flight covering all segments (row 2018_02_09 of Table 1) is shown at left in Figure 4. During this test, ICAROUS re-routed the UAV around two stay-out regions along the North Dryden Street segment during both southbound and northbound legs of the flight. Flight path altitude was level at 40m AGL and speed was 8 m/s (approximately 18 mph).

A non-GPS vehicle position data source was tested at a secondary flight range with known GPS and other RF-related problems. This range was at the Impact Dynamics Research Facility (formerly known as the Lunar Lander Research Facility) which consists of a large steel truss gantry, approximately 180 ft. tall and surrounded on all sides by tall trees. The trees and trusswork attenuate and reflect GPS signals and the mass of ferrous metal distorts magnetometer-based heading readings. Multiple Locata transceivers were installed on the gantry structure, creating an airspace volume in which a stable and accurate alternative to GPS was available. The UAV was flown vertically from within this "Locata volume" up to 110 m AGL where clear line of sight to orbital GPS satellites was available (orange path at right in Figure 4). This allowed recording of vertical transitions into and out of the Locata volume and a "cleaner" GPS volume. Additionally, the UAV was flown laterally from within this "Locata volume" at a moderate (35 m) altitude to adjacent volumes (yellow path at right in Figure 4) to record horizontal transitions into and out of these two types of regions. Such transitions can be anticipated when flying at low altitudes in urban areas (particularly urban canyons).

Inter-vehicle communication (DSRC) hardware was installed on the research octocopter and tested in short flights with a second DSRC-equipped vehicle (i.e., a Tarot hexacopter [13]) flying nearby. These short flights verified the ability of ICAROUS, onboard the octocopter, to sense and avoid the hexacopter by interpreting the DSRC updates and issuing commands to the autopilot.

Figure 4. UTM recordings of two research flights. Left: Research flight across the primary range from the flight date 2017_02_09 testing vehicle chase operations and stay-out geofence maneuvers. Vehicle positions as retrieved from the UTM tracking server are shown as yellow spheres overlaid atop positions as reported by the autopilot, rendered as transparent sheets extending from the flight path to ground. The route-around maneuvers can be seen at the two intersections where stay-out regions were defined. Right: Research flight at the Gantry structure from the flight date 2017_01_24. Vehicle positions as retrieved from the UTM tracking server are shown as orange spheres for a vertical "chimney flight" and as yellow spheres for the lateral flight. © *Map data: Google.*

The test series culminated in comprehensive flights (row 2018_03_28 of Table 1) that combined multiple safety assurance technologies in one flight wherein various hazards were encountered, as previously tested separately. These included: ICAROUS for geofence avoidance, Safeguard for stay-in and stay-out geofence predictive warnings, and V2V/ICAROUS sense and avoid and well-clear enforcement. Figure 5 shows the flight telemetry (blue traces) for one of these flights as the octocopter flew in the waypoint sequence "down and back" (A-B-C-D-D2-E-D2-C-B-A) as shown in Figure 1. Insets in Figure 5 highlight the hazards/conflicts encountered and illustrate the contingency maneuvers undertaken by the onboard autonomy to resolve them:

- Between waypoints B and C, the vehicle encountered a stay-out region and was routed around it by the ICAROUS autonomy (middle right inset).
- Waypoint D was intentionally placed outside the stay-in boundary. The Safeguard warning triggered a series of bounce-back maneuvers (executed by ICAROUS) and then rejected the waypoint, freeing the vehicle to resume flight to the next waypoint (bottom right inset).
- A second vehicle crossed the planned flight path in the final B-A segment, at the north end of the range, and the ICAROUS autonomy adjusted the vehicle heading to avoid a collision (top right inset).

A depiction of this vehicle avoidance maneuver is shown in Figure 6. Autopilot trajectories are shown on the left. The aircraft were deliberately flown at safely separated altitudes; specifically, 60m AGL altitude for the intruder aircraft travelling at 6 m/s (cyan traces), and 40m AGL altitude for the ICAROUS-equipped octocopter travelling at 3 m/s (blue and yellow traces). The collision avoidance maneuver in this case was computed in the lateral plane only using a well-clear radius of 12m and a look-ahead time of 10 seconds. Post-flight simulation plots using recorded data from the encounter are shown at right. The ICAROUS path avoidance decision evolved dynamically from a 90 degree turn from the flight plan heading (T1, top right), through a 180 degree turn, to resumption to the flight plan heading (T2, bottom right). The top right simulation plot (T1) shows the vehicle in a violation state. The red arc represents headings which will prolong or worsen collision risk, and the green arc represents headings that lessen collision risk. The bottom right simulation plot (T2) shows the vehicle in a well-clear state. The dark grey arc represents headings that maintain well clear status, and the red arc represents headings that will result in a violation within the next 10 seconds.

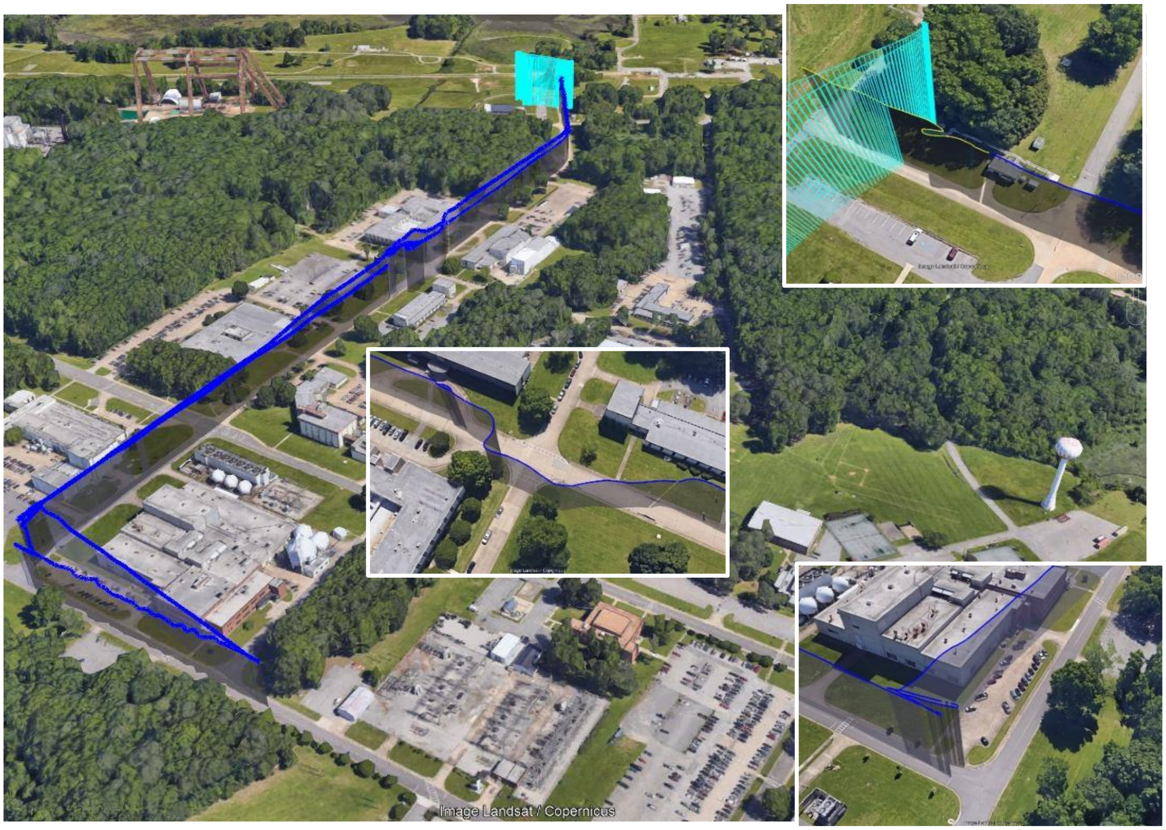

Figure 5. Example of multi-segment comprehensive flight over NASA Langley Research Center's CERTAIN range, from the flight date 2018_03_28. Insets highlight contingency maneuvers executed by onboard autonomy. © *Satellite map data: Google.*

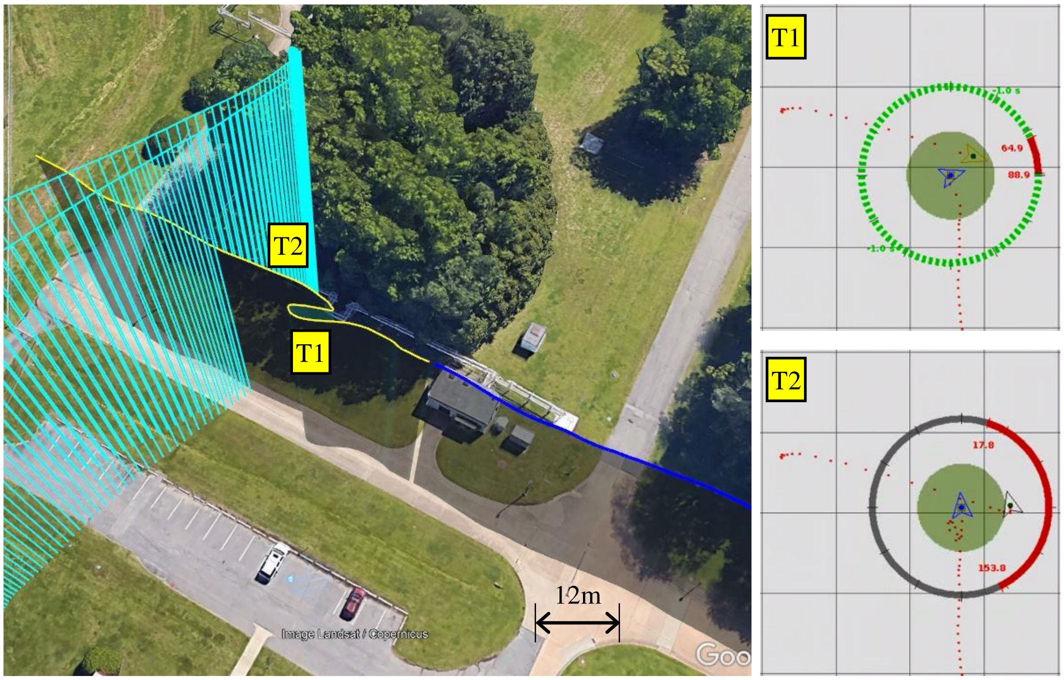

Figure 6. Vehicle avoidance maneuver from the flight date 2018_03_28. The closest allowed radial distance between vehicles was set to 12 meters (scale bar at left, radius of green filled circles at right) and the look-ahead time was set to 10 seconds. Left: autopilot trajectories. Right: post-flight simulation plots using log data from the encounter.

V. Observations

Because the flight series was completed just before this report was prepared, a detailed analysis of results remains ongoing and findings will be published in subsequent reports. However, in general, the aircraft, avionics, integrated air/ground platform, and ground systems all operated as expected, with only minor exceptions. The UTM tracking matched autopilot position telemetry with good fidelity and continuity. No false alarms or missed detections were observed regarding the Safeguard functionality. The DSRC performed well, albeit testing was limited to short range encounters. Its antenna mounting point was carefully chosen to avoid radio frequency interference (RFI) with other aircraft systems. No substantive environmental RFI was observed in any of the flight ranges. On-board and ground computing capacity and throughput was sufficient for all tests.

As with any field operation, non-ideal conditions did arise. For example, wind gusted from time to time, and sometimes battery levels depleted more than expected. GPS reception was sometimes spotty at low altitudes within along Victory Street (between points D and E), at point B (Figure 1), and at the secondary Gantry range.

Two specific tests and evaluations are not discussed in detail here but are the subject of draft reports: (1) the RTRA technology testing, and (2) the navigation system transition testing at the Gantry.

Elements of the data analysis will also address relevant Measures of Performance (MOPs) being defined by UTM project management and the Research Transition Teams (RTTs).

Last, in addition to the technology testing, demonstration, and evaluation, many new procedures were defined and refined in order to conduct the flight tests safely and efficiently. While not a specific objective of the R&D, several best-practices evolved over the test period that can be used in subsequent tests, and may be useful to industry. These cover, for example, pre-flight procedures/checklists, in-flight communications and coordination (GCS operator and RC-based safety pilot), and post-flight data archiving and system shutdown procedures.

VI. Anticipated Extensions

Future tests are planned under two NASA projects. The UTM project proceeds to its TCL-4 test milestone in 2019-2020. The System-Wide Safety (SWS) project which began in late 2018 and runs through 2023 also has flight test milestones involving safety-enablers for future urban sUAS operations and operational elements projected to be relevant to urban air mobility (UAM) missions. As part of these projects, some of the anticipated extensions are:

- Expanded vehicle avoidance. The primary aircraft will avoid the secondary vehicle by changing both lateral and vertical position, for both multi-rotor and fixed-wing secondary vehicles.
- Alternate position system evaluations and integration. In locations with degraded GPS reception, the vehicle will have access to a secondary positioning system (e.g., Locata).
- Expanded range characterization. For example, survey instrumentation can map, model and update environmental radio frequency interference levels and GPS signal obstructions.
- Expanded geofencing of hazards/risks. For example, geofenced obstructions can include terrain features such as trees and buildings.
- In-flight data services. New supplemental data services under development (including the range characterizations just described) can inform the aircraft (or the GCS) of predicted risks or hazards based on the context of each flight.

VII. Conclusion

A suite of airborne and ground-based technologies to advance autonomous sUAS safety in low-altitude urban operations was integrated, tested and evaluated in several dozen research flights conducted at NASA Langley Research Center in 2017-2018. Operations evolved from short segments within line-of-sight of the safety pilot and ground station, over moderately populated land during evenings and weekends, to flights over several city blocks in which the safety pilot maintained line of sight from a chase vehicle during daytime business hours. Operations were conducted in a 1.1 km primary flight range and two secondary flight ranges.

Off-nominal risks were introduced, including stay-in and stay-out geofences and vehicle-to-vehicle encounters, and three contingency maneuvers were demonstrated that provide safe flight responses tailored for the specific risk encountered. These maneuvers made use of an integrated air/ground platform, two on-board autonomous capabilities (ICAROUS, a decision-making framework and technology, and Safeguard, an independent geo-conformance monitor), and a short-range radio interlink system to provide vehicle-to-vehicle position, heading and velocity. From a visual inspection of post-flight data, the on-board autonomous capabilities performed as expected. However, an in-depth analysis of flight data is being performed and will be published in future reports.

Additionally, flights were executed to characterize the Locata positioning system as an alternative to GPS in both clear and GPS-deprived locations. Complex low-altitude trajectories were flown while sensing ultraviolet radiation, to demonstrate a realistic UAV-based infrastructure fault detection mission reinforced with these safety augmentations.

Flight data was monitored and recorded with multiple ground systems and was forwarded in real time to a UTM server for airspace coordination and supervision. Many of the demonstrated advancements are encompassed in UTM Technology Capability Level 3.

VIII. Appendix

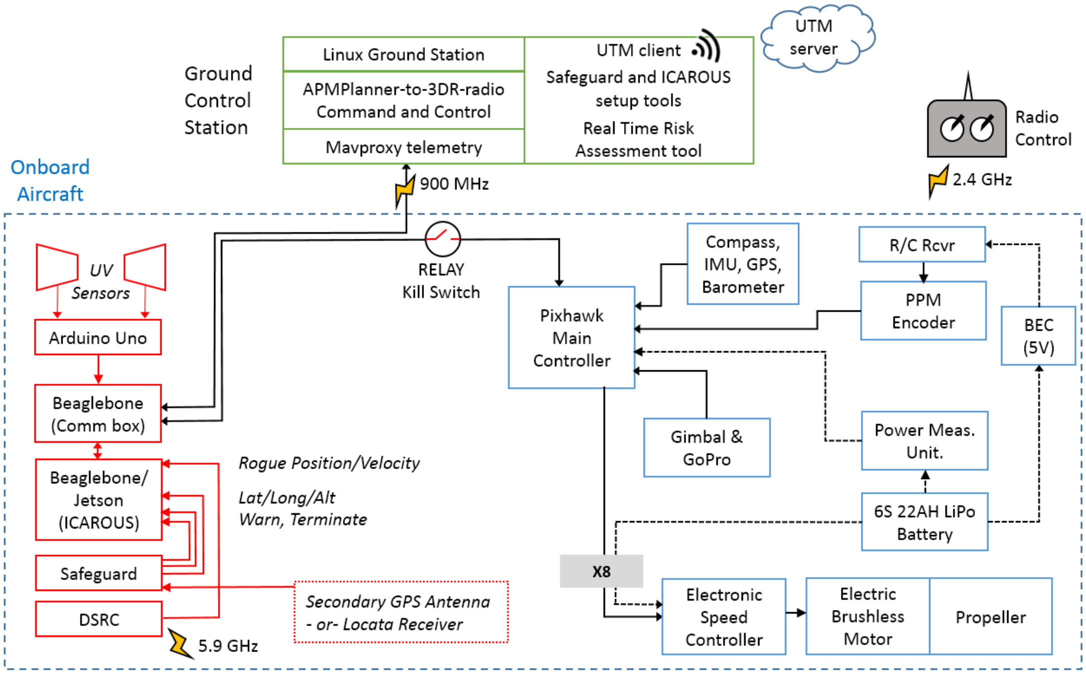

Figure 7. Diagram of integrated air-ground system.

IX. Acknowledgments

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